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Advanced Missile Technology

A Review of Technology Improvement Areas for Cruise Missiles

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A Review of Technology Improvement Areas for Cruise Missiles

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1. Statement of Objective

In keeping with its historic role of providing an advanced technology base in aeronautics, NASA, through its Langley Research Center, has undertaken an assessment of the significance of advanced aerodynamic, propulsion, and structural technology for cruise missile systems. Such an assessment should provide NASA with a rationale for planning a research program in those technology areas, and a nucleus of a plan for such a program. Although the assessment is centered on cruise missile systems, the recommended research programs would undoubtedly have applicability to other missile and aircraft systems. The purpose of this report is to contribute to the assessment and to recommend areas in which research and development effort is needed in aerodynamics, propulsion, and structures over the speed range from subsonic to hypersonic to support the future development of improved cruise missile systems.

2. Definition of Cruise Missile

In this report, a very general definition of a "cruise" missile is taken which includes missiles such as Tomahawk as a sub-class. The "cruise" missile will be defined as one which spends the major portion of its flight trajectory in the "cruise" mode, that is, flying at nearly constant altitude at nearly constant speed using aerodynamic lift to support its weight. Thus, highly maneuverable short range tactical missiles would not be included yet long range tactical or strategic missiles might be included depending on the flight profile. Such a definition emphasizes missiles which are optimized for range and payload capacity rather than those intended to defeat high-speed targets using high speed and high maneuverability; nevertheless, it should be recognized that high speed and/or high maneuverability in the terminal phase of a long or medium range missile flight may be a needed ingredient for penetrativity, that is, for piercing the enemy's defenses and reaching the target.

The assessment covers the long range subsonic cruise missiles (such as Tomahawk), the shorter range subsonic missiles (such as Harpoon) and the supersonic and hypersonic missiles of medium range which may be used in a defensive mode against jamming aircraft, or missile-launching aircraft, as well as in attacking ground-based defenses or high value targets. These latter missiles must cruise at high altitude for most of the trajectory to be able to achieve satisfactory range performance.

The family of cruise missiles under consideration can be categorized by two cruise altitude regimes (high and low), by three speeds (subsonic, supersonic, hypersonic), by three range requirements (short, medium, long), and by mission or target type (tactical, strategic, and defensive or preemptive). The first three of these very general terms can be bounded by representative values given below. These are typical, illustrative, values and should not be taken as absolute ones.

1. Cruise Altitude;

   Low: Terrain following, wave skimming, 60 m or less above surface.

   High: As high as possible, in tens of thousands of feet, to maximize range (fuel efficiency) and speed.

2. Cruise Speed:

Subsonic: $0.5 \le M < 1$

Supersonic: $1 < M \le 4$

Hypersonic: $4 < M < 10$

3. Range:

Short: 80 - 160 km

Medium: 160 - 800 km

Long: 800 - 8000 km

4. Targets:

Surface or medium altitude targets. Against defended targets, the subsonic cruise missiles' likelihood of penetrating to the target can be enhanced significantly by providing it with a supersonic terminal dash option.

5. Missions: Self-explanatory.

A matrix of these cruise missile categorizations is presented in Chart 2-1 in an attempt to highlight likely combinations and typical applications. Representative cruise missiles or concepts are indicated in the missions column by reference to footnotes.

Chart 2-1. Matrix of Cruise Missile Characteristics

Cruise Speed	Cruise Altitude	Range			Mission		
		Short	Medium	Long	Tactical	Strategic	Defensive/ Preemptive
Subsonic (with or without terminal super- sonic dash)	Low	X	X	X	X (1)(2)	X (1)(5)	
	High		X	X		X (1)	
Supersonic	Low	X	X				X (7)
	High		X	X		X (3)(4)(5)	X (3)(6)
Hypersonic	High		X		X (6)		X (6)

NOTES: Representative cruise missiles or concepts:

- (1) Tomahawk, Tomahawk follow-on, ALCM (Air-Launched Cruise Missile)
- (2) Harpoon
- (3) SRAM (Short Range Attack Missile)
- (4) ASALM (Advanced Strategic Air-Launched Missile)
- (5) Advanced Technology for Cruise Missiles (Air Force)
- (6) Stand-off Jammer Intercept Missile (SOJIM), Long Range Dual Mission Missile (LRDMM)
- (7) TTM (Torpedo Tube Missile for Anti-Ship and Anti-Submarine Warfare)

3. Approach to Assessment

In order to assess properly what advantages might be realized by technological advances in aerodynamics, structures, and propulsion, it would be well to establish the current capability, ascertain design limitations resulting from technology lag or incompatible systems requirements, and then evaluate what gains might be achieved by more advanced technology in each area or by fuller consideration of the coupled advantages that might be achieved through system considerations of the relations between the technologies. For example, even though this study does not include guidance and control or countermeasures, these areas must not be ignored in evaluating effects of technological advances in airframe design. An important consideration in a cruise missile system might be to minimize detection or limit the response time of the defense. Such considerations should be included in the advanced technology assessment wherever possible.

3.1 System Requirements and Aerodynamics, Propulsion, and Structures Technologies

It may be helpful at this point to sketch the interactions of aerodynamics, propulsion, and structures with the system requirements imposed on a typical cruise missile by its launch-to-target environment. The example used is that of a long-range subsonic cruise missile but the approach and comments are applicable to other cruise missiles as well.

The sequence of flight of a cruise missile begins in a safe airspace with launch, climb or dive to cruise level, then flight at constant altitude cruise toward the landfall, checkpoint, or target area. As soon as, and preferably before, the safe airspace comes under surveillance by the enemy, the cruise missile may deviate from a fixed heading, constant altitude cruise by maneuvers in azimuth (to deceive the observer) and in elevation (as required for a low altitude terrain-following flight attempting to avoid detection) and thus delay positive early warning and acquisition while flying in the airspace under surveillance. Sooner or later the airspace becomes defended by missile or aircraft interceptors and the cruise missile must continue to fly deceptively to avoid positive and continuous acquisition and tracking by the defenders' optical and radar sensors so as to minimize its potential exposure to interceptor attacks. Only when the missile is close enough to the target that launching an interceptor would be too late, can it initiate a safe, straight-in run toward the target.

Such a flight sequence leads to essentially four system requirements which must be met, namely, a) pre-launch survivability, b) launch-to-target performance (range, time), c) penetrativity, and d) terminal accuracy. These requirements demand specific performance and other characteristics from the airframe design and its contents.

For example, pre-launch survivability is enhanced by mobility of the launcher and rapidity of launch. Thus, minimizing launch weight and maximizing launch thrust through advanced technologies of structures and propulsion, respectively, will enhance this requirement.

The launch-to-target range requirement calls on aerodynamics, propulsion, and structures technologies to provide a configuration with minimum weight, volume, and size to fly the range, R, from launch-to-target. In addition, the straight line or great circle range R must be increased by a factor K_1 to allow for the vertical maneuver required to follow the terrain at low altitude, and by a factor K_2 to allow for the horizontal or "jinking" maneuver required to deceive any observing sensors in the vicinity of the target. The horizontal maneuver can also utilize terrain masking features around the target to reduce the defenders' ability to acquire the missile, track it, and fire interceptors at it. The technologies of aerodynamics, propulsion and structures will be hard pressed to provide a balanced design with adequate range capability, K_1K_2R, and with the low observables characteristics demanded by the penetrativity requirements which will be discussed later.

For some missions, time-to-target performance becomes a significant parameter. Reducing the time-to-target gives the defender less time to react to counter the attack or, if the target is mobile, less time to move it from the original targeting point. For "cruise-type" medium range missiles which defend an area, reduced time-to-target is sometimes necessary to enable the defender to kill the attacker's jammers and missile-carrying vehicles before their missiles can be released. To achieve minimum time-to-target, there is need for highly efficient propulsion, possibly more than one missile stage, minimum drag, minimum structural weight, and an optimized flight path.

Penetrativity is achieved when the defending sensors cannot acquire and track the cruise missile because of its low electromagnetic, infra-red, acoustical, or optical signatures, and when it closes on the target so fast that no

interceptor (or no more than one or two) can be launched against it in time for a likely intercept. Ground-, air-, or space-based early warning systems with their radar and IR sensors attempt to note incoming missiles and to pass on the observed object's speed, track, and altitude to the forward area defenses, barrier defenses, and terminal defenses, all of which have their own internetted, acquisition and tracking sensors with AWACS (Airborne Warning and Control System) and GCI (Ground Controlled Intercept) control systems, fighter-interceptors and surface-to-air missiles. Low signatures are needed to defeat or stress all these defense systems, while high speed is also helpful primarily against terminal defense interceptors. Thus the technologies of structures, propulsion, and aerodynamics must strive to maintain as low an electromagnetic, infra-red, acoustical, and optical signature of the airframe as possible. The same demands apply to whatever active sensors are used in the cruise missile to accomplish terrain recognition and following. The high terminal speed desired involves principally only propulsion and aerodynamic technologies.

Note that aerodynamics, propulsion and structures can have a synergistic contribution to penetrativity by providing a low signature for the basic missile, and by contributing to low observability through provision of maneuvering capabilities for low altitude terrain following, deceptive meandering toward the target, and terrain masking flight into the target, all of which require exceptional performance in lift, drag, thrust, and fuel consumption.

The fourth system requirement, that of terminal accuracy, depends on adequate performance in the domain of sensors, computers, data storage, fuzing, and dynamic system response, the latter being the only area wherein aerodynamic and structural characteristics affect the overall system response. In addition, sensor and fuzing systems may require advanced materials technology to provide window materials whose transmittability will not deteriorate with flight time and environment.

These cruise missile system requirements can be translated into performance characteristics which are driven by the various technologies mentioned above. Future cruise missiles will require improved performance characteristics which in turn will depend on technological advances, generally in more than one area. An attempt will be made to relate performance improvement areas to typical improvement factors which depend on the various technologies and advances therein.

Before doing so, however, it must be recognized that in addition to performance characteristics, there exist equally important economic characteristics, such as cost (of development, production, and operation), simplicity of the system (requiring less training of operating personnel), and logistic considerations (in subsystems, components, parts, material, etc.). These economic characteristics can be strongly affected by some of the same technological factors which control performance characteristics.

Hence, both performance and economic improvement areas can be related to various contributing factors which depend on the capabilities of one or more technological areas.

3.2 Improvement Areas, Technology Involvement, and Contributing Physical and Design Factors

Performance improvements generally place demands on physical factors by requiring operation at higher speeds, or over a broader range of altitudes, or with greater maneuverability, or with lower signatures, weight, or volume, most of which are costly, i.e., affect economics adversely. On the other hand, economic improvements, such as lower total (or life cycle) cost may mean sacrificing some performance characteristics without compromising the basic mission requirements significantly. Hence, some balance must be found between performance and economics in application of advanced technologies.

To help find such a balance, an attempt has been made in Chart 3-1 to relate performance and economic improvement areas to various contributing factors which in turn depend on the output of one or more technologies. The majority of the contributing factors listed are "physical" in nature and are so identified. The last three factors are design goals which have a major impact on economics and are listed as "design" factors. Some of these factors, however, can also have an impact on performance. For example, an easily-produced material for thermal protection or for radar absorption may lose its protective characteristics much faster than desired for the life of the system, or it may require special (and costly) environmental protection or special handling in order to retain its intended performance characteristics.

As stated earlier, the physical and design factors, which make demands on the technologies if improvements are to be made in the areas described in Chart 3-1, will influence the priorities in assessing those improvement areas (Section 6) and in recommending technology research programs (Section 7).

Chart 3-1. Improvement Areas and Related Contributing Factors

Contributing Factors / Improvement Areas	Physical								Design		
	Observables	Cruise Speed	Altitude	Axial Maneuver	Lateral Maneuver	Weight	Volume	Launcher Constraints	Producibility	Maintainability	Operability
Performance											
Penetrativity	A P S	A P S	A P S	A P	A P S	-	A P S	A P S	S	S	X
Range	-	A P	A P	-	-	A P S	A P S	-	-	-	-
Time-to-Target	-	A P S	A P S	A P	-	A P S	-	-	-	X	X
Terminal Accuracy	-	A P S	-	A P	A P S	A P S	-	P S	-	X	X
Pre-Launch Survivability	-	-	-	P	-	S	-	P	-	X	X
A = Aerodynamics, P = Propulsion, S = Structures (Materials)											
Economics											
Cost	X	X	X	X	X	X	X	X	X	X	X
Simplicity	X	X	X	X	X	-	X	X	X	X	X
Logistics	X	-	-	-	X	X	X	X	-	X	X
X = One or More Technologies											

In addition to noting in the matrix of Chart 3-1 those "physical" and "design" factors which are most influential in achieving improvements in performance or economics, the technology (or technologies) are identified which require most consideration in each case. For example, improving penetrativity requires moving with stealth (observables) as quickly as possible (speed) and along a path on which detection is made difficult (altitude). To further enhance penetrativity, a "speed-up" capability near the target area and a capability to outmaneuver a defensive missile should be considered. The factor "observables" requires work in aerodynamics to design efficient airframes with low sensor signatures (e.g., low radar cross-section); in propulsion, to design inlets with low radar cross-section, to minimize the noise from the entire propulsion system, and to decrease the infrared signature from the engine and its exhaust; and in structures and materials to develop airframes using radar absorbing primary structure (RAPS) or applications of radar absorbing material (RAM) which do not penalize performance of the other technologies. The factors "speed" and "altitude" to increase penetrativity must also be considered by all three technologies since they usually influence the geometry of the aerodynamic configuration, the size and type of propulsion system, and the materials and structural methods used in building the airframe. The most likely axial maneuver to increase penetrativity is a "dash phase" in the terminal approach to the target, requiring an increased propulsive capability and, possibly, aerodynamic modifications for a relatively short period. An aerodynamic configuration which can provide lateral maneuvers with quick response to evade defensive missiles (with appropriate help from propulsion and structures as well) is also an important factor for improving penetrativity.

A small volume enhances penetration but puts a further demand on the three technologies being considered because this factor usually implies a higher density missile to achieve the mission. Smaller engines with higher density fuel, more effective lift with smaller lifting elements, and less allowable volume for structural material are challenges to the technologies.

Similarly, launcher constraints (other than weight and volume) such as allowable shape, span, compatibility with the carrier, etc., result in similar demands on the three technologies.

The design factors affecting penetrativity require that the structure (material) be produced and maintained to the required signature

characteristics. Actual operation with enhanced penetration capability requires consideration of one or more of the technologies involved depending on the specific design approach used. This less specific relationship is denoted by X in Chart 3-1.

In the case of range improvement, the significant parameters are generally speed, weight, flight path (altitude), specific fuel consumption, lift and drag. In contrast to penetrativity, speed and altitude here embrace primarily aerodynamics and propulsion, while structures as well as aerodynamics and propulsion contributes to the weight and volume factors.

When time-to-target is a governing condition (as in some medium-range defensive missile systems), speed, optimum altitude, axial acceleration, and minimum weight are the contributing factors to be considered. These factors usually have a greater impact on the propulsion system design but they do also affect the aerodynamic and structures technologies as shown in the Chart. Design considerations for maintainability (in storage or readiness) and operability (under field conditions) apply to this area and may affect one or more of the technologies.

Terminal accuracy, as noted previously, requires good dynamic response which, in turn, is dependent on speed, axial and lateral acceleration, and to a lesser extent, weight and its distribution. Lateral maneuverability requirements have a major impact on the aerodynamic configuration. The launch constraint must call on propulsion and materials (structures) to avoid contamination of guidance and terminal sensors required for terminal accuracy. Maintainability and operability must be equally designed for in this area.

Pre-launch survivability can be best achieved by concealment or mobility of the launch site and/or by rapidly launching the missiles on the assigned missions. The latter item can be improved by minimizing take-off weight and maximizing take-off thrust. These objectives relate directly to structures and propulsion, respectively. However, propulsion and structures are also depended upon not to degrade prelaunch survival due to the environment of a constrained launch. Design considerations for maintainability and operability apply in this area as well.

In the case of improvement areas in Economics, the discussion will concern the impact of the contributing factors in a general way (indicated by X in Chart 3-1) since the primary recommendations for technology investigations are related to performance improvements rather than cost reduction. The latter field would be handled more appropriately by an organization with experience in production techniques.

Any effort to change the observables (radar, acoustic, infrared, visible, etc.) by geometric modification, coatings, material changes, etc., is likely to lead to a more complex design which would be more costly to produce and maintain operationally. Design for higher speed would lead to increased requirements on the engine and, accompanying the higher speed, the higher temperature would usually require improved materials, particularly if the higher speed missile must operate at low altitudes. Thermal protection generally affects simplicity of design and adds to cost.

The need for axial maneuverability, that is, the ability to speed up or slow down, can be achieved by variable geometry in the propulsion system and/or control of fuel rate. For air-breathers, variable geometry inlets and exit nozzles, and for rockets, variable burning rates and variable geometry nozzles, add complexity and cost.

Lateral maneuverability can be improved through addition of lifting surface area or operation at higher angles of attack, assuming given speed regimes. Larger lifting surfaces can add to logistics problems and operation at high angles of attack adds dynamic complexities resulting from aerodynamic coupling.

Generally, any reductions in weight and/or volume would be expected to improve logistics problems. They may in some instances, however, lead to increased costs in production if, for example, the decrease in volume results in denser sub-systems which are more difficult to assemble. For the same reasons, launcher constraints on weight, volume, or geometry sometimes force the design into a less than optimum configuration with more complex arrangements for accomplishing the mission. For example, restricted span for aerodynamic surfaces in a launching system may require use of folding and unfolding mechanisms for the surfaces.

The design factors of producibility, maintainability, and operability are obviously the strongest influences on the economic areas.

4. Review of Technology

4.1 Foreign Missiles

A review of the medium- and long-range missiles in the USSR arsenal (Refs. 4.1, 4.2, 4.3, 4.4) indicates that generally the designers are not pushing the state-of-the-art but rather are using proven components, assembling them in missiles to accomplish some specific missions and deploying them as early as possible. It does not appear that much consideration has been given to penetrativity, that is, reducing susceptibility to being detected, tracked, and intercepted before completing the mission. At the time of deployment of many of these weapons (1960's), however, there was probably little concern for such a problem since there were no very sophisticated defense systems.

The earlier air-to-surface and surface-to-surface missiles of the "cruise" type such as the AS-1 (Kennel) and SSC-2B (Samlet) used turbojet engines at high subsonic speeds in airplane-like configurations with swept wings. Later missiles designed for high speeds retained the airplane-like configuration and used improved turbojets or liquid rockets for propulsion, achieving speeds in the low supersonic range.

Two other missiles which should be noted are the French-Italian OTOMAT with cruciform wings and tails and the Swedish RB08A, an outgrowth of an airplane-like drone. Both are high subsonic turbojets boosted to cruise speed by separable solid rocket boosters.

There is no indication that any of the missiles listed in Chart 4-1 have used any advanced technology in aerodynamics, propulsion, or structures.

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CHART 4-1

Some Foreign Air-to-Surface and Surface-to-Surface Missiles

Designation	Propulsion	Speed	Range	Configuration
		USSR		
AS-1 (Kennel)	Turbojet	M = 0.9	100-110 km	Airplane-like, frontal chin inlet
AS-2 (Kipper)	Turbojet	M = 1.2	180-215 km	Airplane-like, underslung engine
AS-3 (Kangaroo)	Turbojet	M = 2	185-650 km	Airplane-like, swept wings
AS-4 (Kitchen)	Liquid Rocket	M = 3.5	460 km	Airplane-like
AS-5 (Kelt)	Liquid Rocket	M = 0.9 ?	160-320 km	Airplane-like
SSC-2b (Samlet)	Solid Rocket Booster Turbojet Sustainer	M = 0.9 ?	80 km	Airplane-like, frontal chin inlet
SS-N-1 (Scrubber)	Solid Rocket Booster Turbojet Sustainer	Subsonic	110-210 km	Airplane-like
SS-N-3 (Shaddock)	Solid Rocket Booster Airbreathing Sustainer	M = 0.9 - 1.4	270-470 km	Airplane-like underslung booster
		France - Italy		
OTOMAT	Solid Rocket Boosters Turbojet Sustainer	M = 0.9	60-110 km	Cruciform wings, tails, and mid-body inlets
		Sweden		
RB08A	Solid Rock Boosters Turbojet Sustainer	M = 0.85	240 km	Airplane-like, frontal chin inlet, two underslung boosters

4.2 U. S. Missiles

Some representative U. S. missiles (both air-to-surface and surface-to-surface) have been listed in Chart 4-2 (Refs. 4.1,4.2,4.3,4.4) to exemplify the types of missiles to be examined for improvement potential based on advances in technology.

The operational missiles, Hound Dog and SRAM, were designed to achieve high speeds with the then available rocket and turbojet propulsion and fuel technologies and used fairly conventional structural and aerodynamic approaches. Efforts at reducing radar cross-section (RCS) were applied to the SRAM configuration from the beginning of development (Ref. 4.5) while the Hound Dog was "cleaned up" electromagnetically in a retrofit effort (Ref. 4.5).

The operational Harpoon, and the ALCM and Tomahawk, currently under development, benefitted essentially from two technological advances over the past ten years. First, the significant, breakthrough-like combination of modern microprocessor technology with advanced terminal sensors and the development of the TERCOM guidance and navigation system which provided autonomous navigation and enhanced low altitude penetrativity even in the subsonic speed regime of these missiles. Second, the advances in small turbojet and turbofan engines and fuel improvements made possible the significant range capabilities of the relatively small ALCM/Tomahawk family of missiles.

Again, consideration has been given to incorporating techniques for lowering the RCS of the basic ALCM and Tomahawk configurations, including the use of radar absorbing materials (RAM). Although some optimization studies were used during the design stages of these missiles, no real advances in aerodynamics were needed to provide the desired airframe characteristics. The structural technology used appears to be quite conventional except for the use of RAM to achieve the desired RCS goals.

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CHART 4-2

Some U. S. Air-to-Surface and Surface-to-Surface Missiles

Designation	Propulsion	Speed	Range	Configuration
AGM 84A (Harpoon)	Solid Rocket Booster (ship launch) plus Turbojet Sustainer	M = 0.9	60 km (ship launch) 200 km (air launch)	Cruciform wings/tails tail control flush inlet
AGM 28B (Hound Dog)	Turbojet	M = 2+	970 km	Supersonic aircraft with canards underslung engine
AGM 69A (SRAM)	Two-pulse solid rocket	M = 3.5+	60-160 km	Supersonic body, 3 fin tail control
AGM 86 (ALCM)	Turbofan	M = 0.7	2200-2400 km	Airplane-like, swept wings, topside engine
AGM/BGM-109 (Tomahawk, SLCM, GLCM)	Solid Rocket Booster (surface launch) - Turbofan	M = 0.7	3200 km (strategic) 500 km (tactical)	Airplane-like, straight wings underslung engine inlet, cruciform tail control

4.3 Some Current Research Activities Related to Cruise Missile Technology

A current four-component program, sponsored by the Defense Advanced Research Projects Agency (DARPA), addresses several of the improvement areas noted in the matrix of Chart 3-1.

One component is devoted to the technology of cruise missile detection in order to better understand the phenomena used in detecting cruise missiles. A related component, dealing with missile configurations, has as its objective the improvement of missile survivability (through stealth) and an increase in range and payload capability. The importance placed on penetrativity is noted by the emphasis on understanding the potential methods of detection and then trying to design missiles to minimize their detectability.

One of the technology areas receiving attention in another component of the program is that of propulsion. The objective here is to reduce the thrust specific fuel consumption from that of present turbofans. Two new engine concepts are under investigation: (1) a compound-cycle turbofan by the Garrett Air Research Corp., and (2) a three-spool turbofan with one off-axis spool by the Teledyne-Ryan Co.

An improvement in terminal accuracy through development of an autonomous terminal homing system constitutes the fourth element of the DARPA program.

The U. S. Air Force has also been supporting investigations in Advanced Technology for Cruise Missiles (ATCM) with contracts at Boeing Aircraft Co., McDonnell Douglas Astronautics Co., General Dynamics/Convair, Rockwell International, and Martin Marietta. Research is, or will be, supported in several areas of aerodynamics, propulsion, and structures and materials based on the needs pointed out by several mission-effectiveness studies. These research areas include investigations of radar absorbing primary structure (RAPS) as well as the use of radar absorbing material (RAM) for coating a primary structure to reduce the radar cross-section (RCS). Research on advanced composites continues to receive strong support.

In aerodynamics, a study entitled "Aero-configured Missiles" has been under way at McDonnell-Douglas-East. The objective of Phase I is to provide upper bounds on available lift-drag ratio, L/D, maximum lift coefficient, $C_{L_{max}}$, and minimum drag coefficient, $C_{D_{min}}$, that an aerodynamic configuration can achieve if no limitations are placed on the design. Although aimed at the supersonic-hypersonic speed regime, some transonic work is included. The characteristics of the numerous configurations are predicted by means of available computer programs and checked by wind tunnel tests at the Arnold Engineering Development Center (AEDC) wind tunnel facilities.

The second phase will narrow the configuration choices by introducing the effects of propulsion systems. The third phase will introduce further missile system limitations, including requirements for reduced radar cross-section. The latter consideration has actually had some influence on Phase I.

The propulsion program includes studies of changes in supersonic inlet design to improve RCS, tests of woven-carbon-carbon material for the walls (without insulation) of conventional hydrocarbon-burning ramjet combustors in supersonic missiles, and studies of carbon slurry and boron slurry fuels.

As noted above, the structures work is concentrated on research on advanced composites and on the use of radar absorbing primary structure. The importance being placed on decreasing radar signatures is noted by the fact that RCS studies have been made on several missile configurations as well as studies of the effects of high temperature on RAM.

A review of the U. S. Navy's activities in missile aerodynamics, propulsion, and structures, as reported in the annual reports of the Navy Aeroballistics Committee (e.g., Ref.4.6) indicates that some work is being done in several areas applicable to the development of "cruise" missiles. In the Advanced Long Range Air-to-Air Missile (ALRAAM) program, low cost production-quality ramjet inlets were evaluated by comparison with wind-tunnel quality inlets and the results indicate that satisfactory performance was provided. Several on-going programs are concerned with development of improved supersonic inlets for turbojet, ramjet, and rocket-ramjet missile applications.

Since both medium and long range supersonic cruise missiles will depend on air-breathing propulsion, these missiles must achieve efficiency through a coordinated development of the propulsion system and the aerodynamic configuration. Some of the stringent launcher constraints of the Navy systems put a further premium on this coordinated approach being taken. Investigations are also under way on ablative liner material for thermal protection in ramjet combustors.

Another area of general interest is the evaluation of effects of erosion resulting from rain or dust or of aerodynamic heating on both mechanical and electromagnetic properties of radomes.

In order to obtain experience with missile wings of composite materials, the Tomahawk contractor has been authorized to develop such a wing. Lighter weight and a reduced radar cross section are expected to result from this application.

In the case of structures and materials for hypersonic missiles, particularly for leading edges, combustors, and nozzles, material screening has been under way to select those materials with properties suitable for the environments to be experienced. In some cases, properties of candidate materials have not yet been characterized over the full temperature range needed.

Because of the span limitations in existing launching systems and those under development, wrap-around and/or folding surfaces are being studied for several missile applications since they offer potential advantages in packaging efficiency.

In summary, there is a modest amount of support in technology development which is applicable to missiles in general with some of the programs specifically directed toward potential improvements in cruise missile systems.

4.4 References

4.1 Jane's Weapons Systems, 1978.

4.2 The World's Missile Systems, General Dynamics, Pomona Division, First Edition, February 1975; Fourth Edition, September 1977.

4.3 Aviation Week and Space Technology, March 13, 1978.

4.4 "World Missile Survey," Flight International (London), May 8, 1975.

4.5 G. A. Taylor, "Missile Radar Camouflage Applications (U)," Confidential Paper No. 18 published in Proceedings of the 1975 Radar Camouflage Symposium (U), December 1975, AFAL-TR-75-100 (SECRET).

4.6 Annual Report of the Navy Aeroballistics Committee to the Naval Air Systems Command and the Naval Sea Systems Command for 1977 (U), August 1978 (Confidential).

5. Potential Areas for Advances in Technology

A relationship between improvement areas and contributing technology factors was suggested in Section 3 (Chart 3-1). In this Section, specific topics of research and development in aerodynamics, propulsion, and structures and materials are assembled into three lists which are thought to contribute to the desired performance improvements. It should be recognized that advances in one technology area will likely have some effect on the other technologies. Furthermore, some areas require a coordinated effort in several technologies to achieve the sought-for improvements. Finally, the need for considering economic improvements as well should not be overlooked but will not be specifically discussed here as that has been done in Section 3.

A review of Chart 3-1 shows that range and time-to-target improvements involve many of the same technologies. The same is true for improvements in terminal accuracy and pre-launch survivability, both implying improved maneuverability. To simplify the subsequent discussion, the areas of terminal accuracy and pre-launch survival have been combined into maneuverability and the range area now includes the time-to-target area. Hence, the five improvement areas listed in Chart 3-1 reduce to three, namely, Penetrativity, Range, and Maneuverability. In Charts 5-1, 5-2, and 5-3 these three improvement areas are related to several topics of research made up of specific items listed by letter and number of the technology items given on the following pages.

In these lists, the numbering does not imply order of importance which can only be attempted after discussing relative merits in Section 6. Furthermore, the priorities will depend on specific missiles designed to meet specific mission requirements.

A subsequent Section (Section 7) suggests technology programs of sufficient importance to future cruise missile development that they may be considered high priority research topics.

Aerodynamics

A-1 Measurements of radar cross-section (RCS) and relevant aerodynamic characteristics of configurations and their components (bodies, fixed and movable surfaces, protuberances, depressions, gaps, fillets, radii of leading and trailing edges) and trade-off studies between RCS and aerodynamic effectiveness for modifications in geometry or location of these components.

A-2 Development of computer programs for use in design trade-offs between RCS and aerodynamic performance.

A-3 Airframe-engine integration with or without decreased RCS as a constraint.

A-4 Optimization of the flight efficiency parameter V(L/D), where V = speed, L = lift, D = drag, particularly for supersonic cruise, to improve range; also, optimization of L/D for flight at constant altitude with lift being decreased in proportion to fuel usage.

A-5 Investigation of potential L/D ratios for supersonic/hypersonic cruise missiles of generic type.

A-6 Methods of wind-tunnel simulation of hypersonic air-breathing missiles, accounting for internal and external viscous effects.

A-7 Convective heating studies on missile components in supersonic-hypersonic regime to account for flow field modifications resulting from roughness, vorticity, shock interaction, slip lines, unsteady flow.

A-8 Development of high lift devices which, when deployed, will not affect significantly the basic low RCS silhouette.

A-9 Continued research in aerodynamics at high angle of attack and in methods of reducing or controlling dynamic coupling resulting therefrom.

Propulsion

P-1 Measurement of radar cross-section (RCS) and propulsion performance parameters (mass capture, pressure recovery, cowl drag, degree of flow uniformity into engine) of inlets of varied shapes and body locations and trade-off studies between RCS and inlet performance.

P-2 Measurements of RCS and propulsion performance parameters (effective thrust, acceleration capability) of varied exhaust nozzle shapes and afterbody geometries and trade-off studies between RCS and nozzle performance.

P-3 Further development of fuels (liquid, liquid plus additives, and solid) to improve energy per unit volume or weight, to increase density, to improve physical characteristics (strength, safety, combustion efficiency).

P-4 Improvement in engine performance through use of variable geometry in nozzles and inlets.

P-5 Development of nozzle-less rockets to increase solid propellant mass fraction.

P-6 Development of simple, smooth and rapid transition from rocket to ramjet operation in integral rocket-ramjet propulsion systems, and optimization of staging.

P-7 Improvement of inlet capability at angles of attack and yaw including development of advanced computational techniques to permit preliminary design of inlets in non-uniform flow fields (resulting from body or wing interference, angle of attack or yaw).

P-8 Development of computer programs for boattail and power-on base flow fields to aid in optimizing the airframe-nozzle integration.

P-9 Development of structural and insulating materials and cooling techniques capable of permitting engine operation at higher temperatures.

P-10 Cycle and design improvements to turbo-engines.

Structures and Materials

S-1 Development of analytic methods (verified by suitable experimental data) to aid in structural design trade-offs among load-carrying capability, thermal protection, and reduced radar cross-section.

S-2 Development of primary structures using radar attenuating material, and comparison with non-radar-attenuating primary structure which uses coating material for reducing radar cross section.

S-3 Compilation of a handbook of data on the advanced composite materials including physical properties relating to load-carrying ability, electromagnetic or thermal absorption, changes in physical properties with environmental conditions, and failure criteria.

S-4 Development of low-cost fabrication methods, process technology, methods of attachment, methods of stress analysis and criteria for instability and buckling of advanced composite materials when applied to missiles.

S-5 Studies of effects of rain, dust, or other particles on the structural integrity and transmittability of sensor domes and of means for reducing these effects.

S-6 Improved definition of the shock and vibrational inputs as well as any fluid dynamics, inertial, and thermal loads imposed by the cruise-missile carriers (aircraft, ships, or submarines).

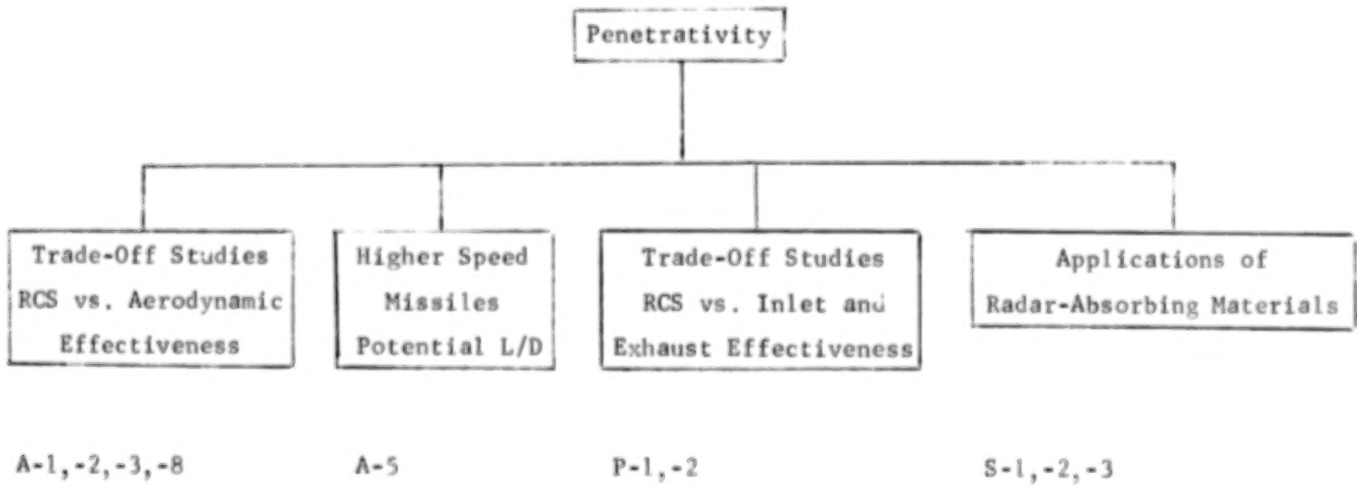

Chart 5-1 Technology Improvement Areas Related to Penetrativity

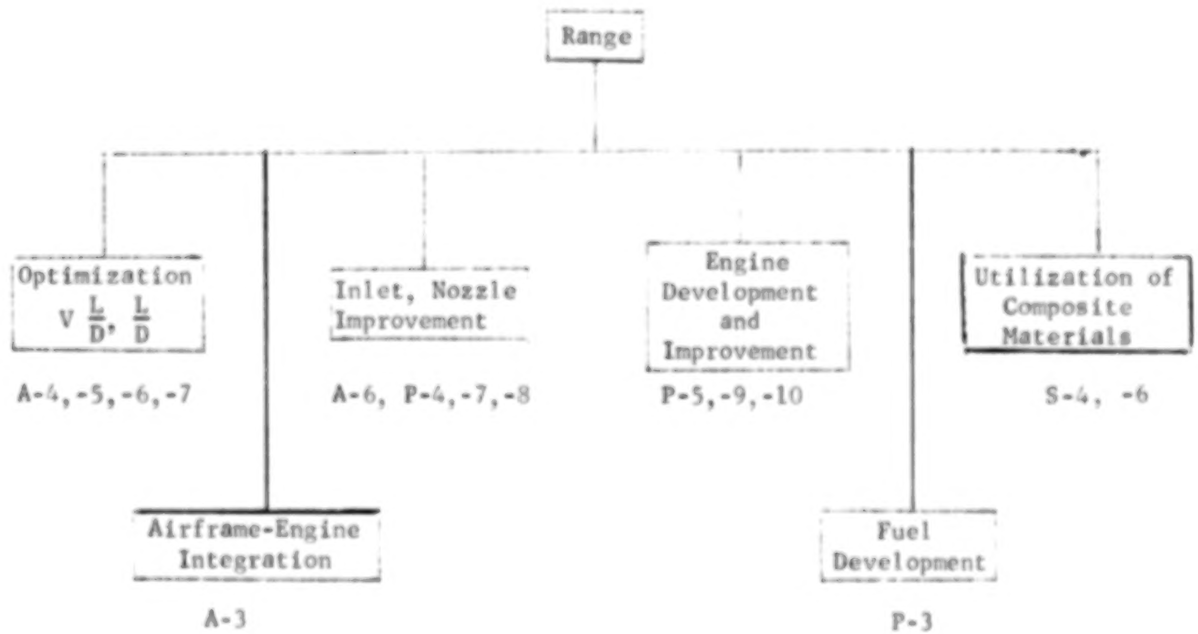

Chart 5-2 Technology Improvement Areas Related to Range and Time-to-Target

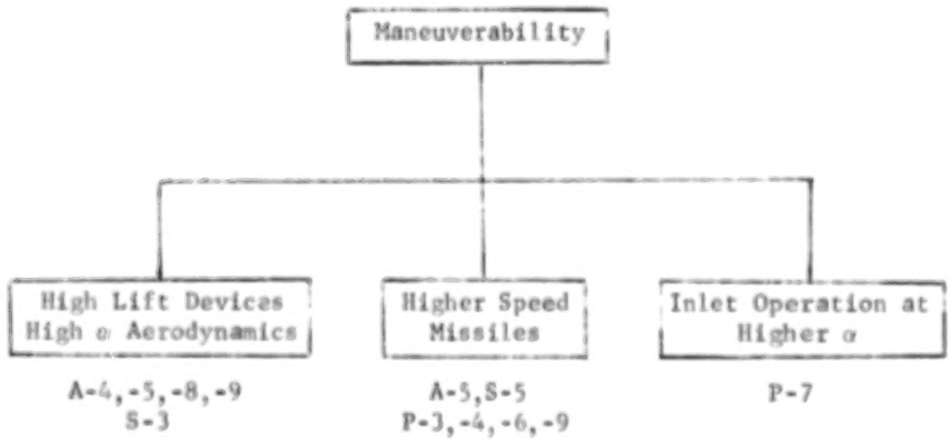

Chart 5-3 Technology Improvement Areas Related to Maneuverability, Terminal Accuracy, and Pre-Launch Survivability

6. Assessment of Potential Improvement Areas

In most cases, quantitative assessments of performance improvements resulting from advances in technology are difficult to make without application to a specific missile designed for a specific mission. Even more hazardous is the forecasting of expected results from research studies in a technology area which one expects to apply to such a missile system. In this Section, the potential improvement areas of Section 5 are discussed in more detail, backed up whenever possible by illustrations of related work or projections based on past experience. It is hoped that such a discussion will suggest the relative merits of the various improvement areas with the ultimate objective of selecting in Section 7 several research areas considered to have the greatest benefit to improved performance of future missiles.

6.1 Aerodynamics

In Items A-1, A-2, and A-3 of Sec. 5 the need is pointed out for investigation of radar cross-section of various configuration elements. Since reduced detectability is becoming more and more important as defensive systems become more sophisticated, the strategic missile designer might be faced with a compromise between a highly efficient missile airframe and propulsion system with undesirable radar cross-section (RCS) or an acceptable radar cross-section for a somewhat less efficient missile. This dilemma indicates the need to be concerned about RCS from the outset of the missile design as emphasized in Ref. 6.1, and in Chart 3-1 of this report.

The major echo sources for missiles nose-on are the inlets (if air-breathing) and the radome section; from the tail-on aspect, the principal echo is from the exhaust nozzle; and from broadside the echo comes mostly from the vertical tails and the side of the body. Generally, one is more concerned with the higher frequency radars where the wave length is small relative to missile size. Some illustrations of RCS measurements are given in Figs. 6-1 and 6-2 taken from Ref. 6.2, and Fig. 6-3 taken from Ref. 6.3 (see footnotes in Sec. 6.4). Shown in Fig. 6-4 taken from Ref. 6.4 is a caution to the designer about the effect of surface irregularities resulting in scattering of incident energy which contributes to RCS.

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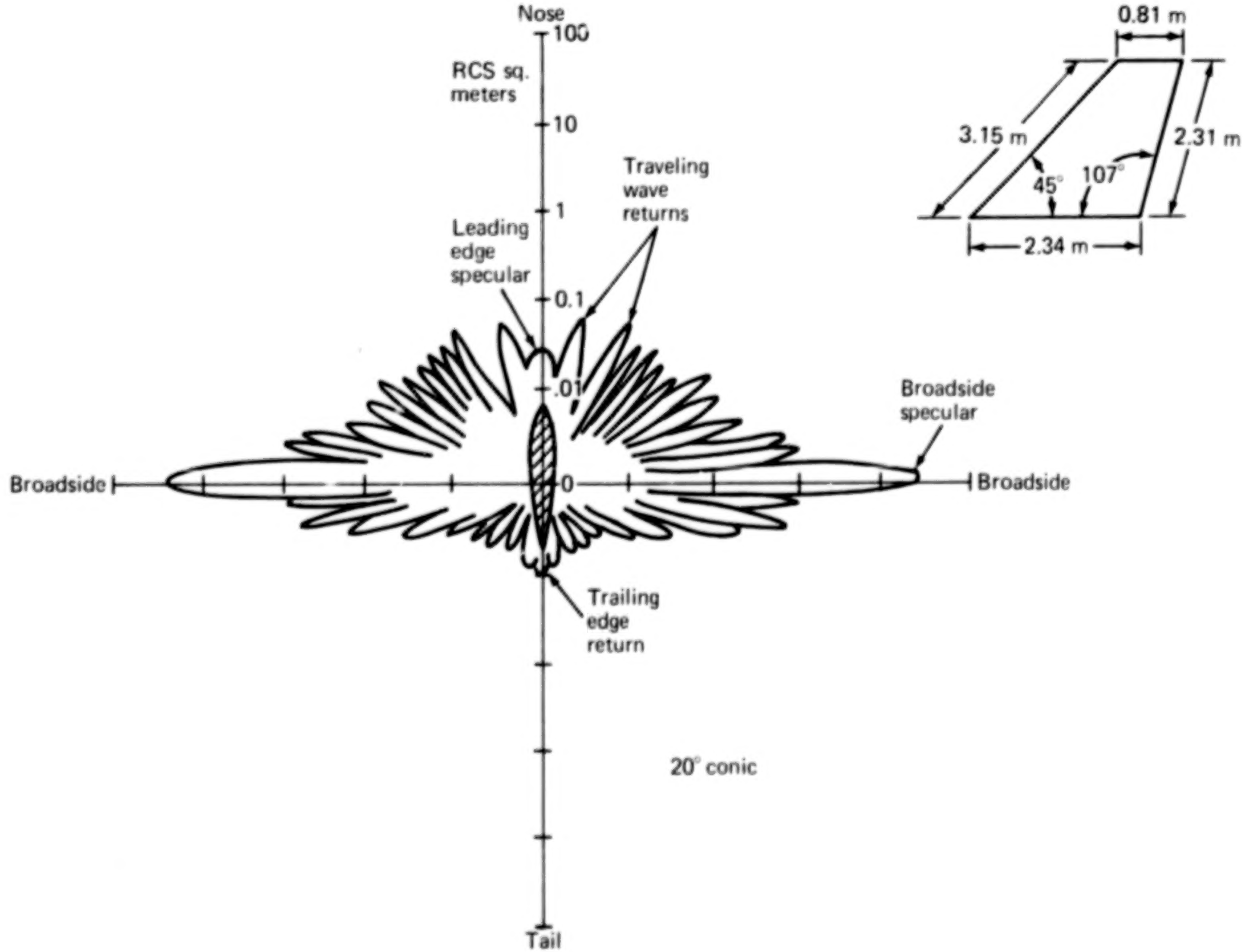

Fig. 6-1 RCS characteristics of vertical tail

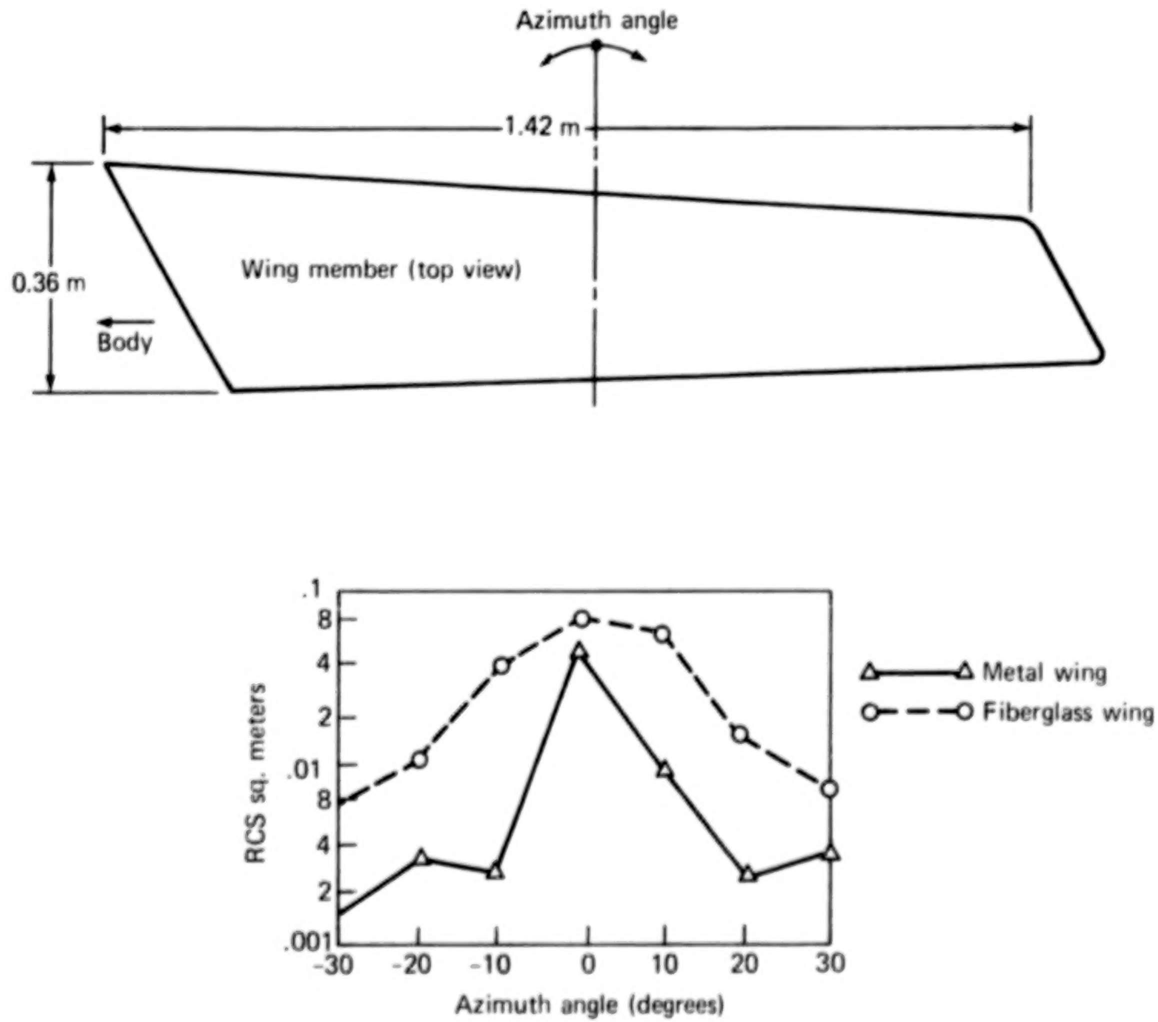

Fig. 6-2 RCS comparison of metallic vs. fiberglass wing

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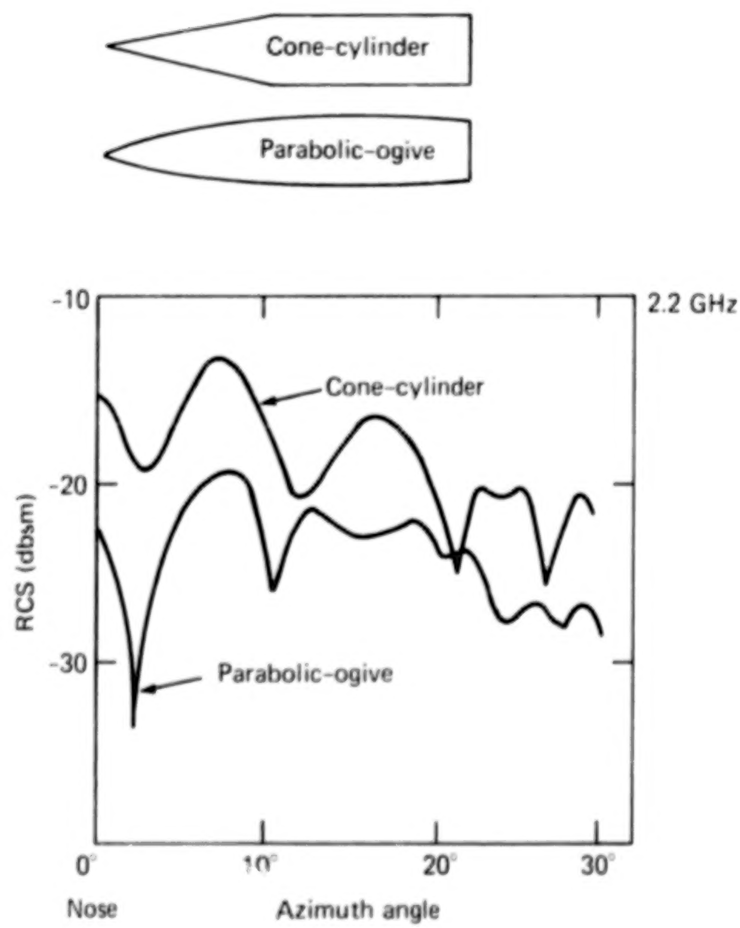

Fig. 6-3 RCS effects of forebody shape

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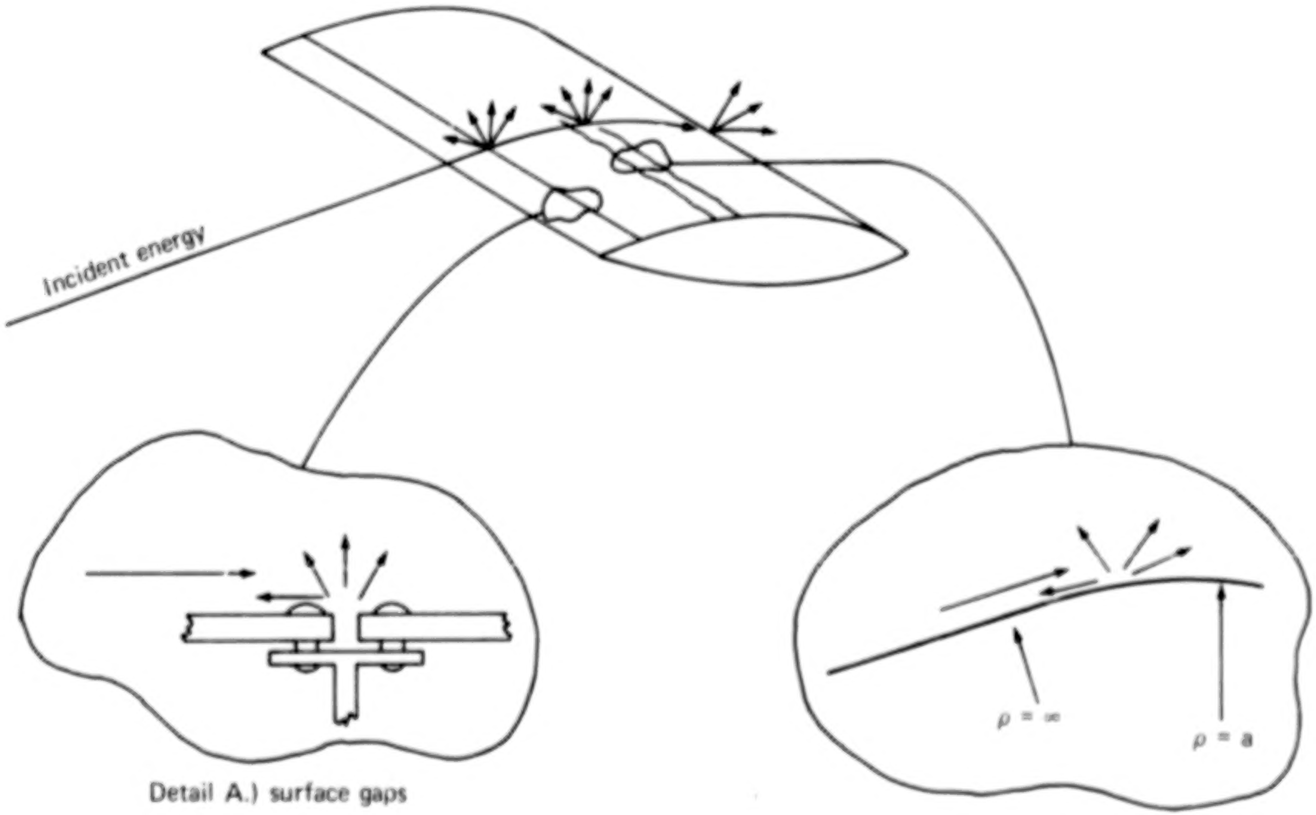

Detail A.) surface gaps

Detail B.) change in surface curvature

Fig. 6-4 Surface irregularities

Further effort along these lines is needed to point the way toward appropriate choices of aerodynamically satisfactory elements for the configuration which will tend to decrease the RCS. In addition, development of simplified analytic methods and computer programs are needed to guide the preliminary design in establishing a suitable compromise between aerodynamic efficiency and reduced radar cross-section.

As an example, a comparison of the supersonic wave drag at zero angle of attack for the two nose shapes shown in Fig. 6-3 (cone and parabolic ogive) was made using data from Ref. 6.7. At Mach numbers between 1.8 and 2.5 the ogival shape has only 60% of the drag of the conical shape so that in this case both radar cross-section and aerodynamic drag benefit by the change in shape from conical to ogival. In many cases the designer will not be this fortunate.

Although the above discussion has concentrated on radar signatures, similar recommendations could be made for other types of signatures, such as infrared.

Item A-3 applies equally well to both aerodynamics and propulsion in that it seeks to emphasize the use of "favorable interference" by a coordinated design. The engine inlets can profit by precompression from the presence of a wing or adjacent body and the airframe lift can be augmented by using external ducting or engine pods as lifting elements. Another area for integration of propulsion and aerodynamics is in the design of the aft section including the nozzle, boattail, and base in order to reduce aft-end drag and maximize engine thrust.

One of the important factors in cruise missile range is the flight efficiency V(L/D) (Item A-4), which appears in one of the Breguet range formulas

$$R = \frac{V(L/D)}{SFC} \ln\left(\frac{W_o}{W_E}\right)$$

where SFC = average specific fuel consumption, 1/sec

W_o = initial missile gross weight, kg

W_E = final missile gross weight, kg

V = speed, m /sec

L/D = lift-to-drag ratio

For subsonic cruise missiles, cruising at very low altitude, some overall improvement may be achieved by the accumulation of several small improvements. For example, as discussed in Ref. 6.5, the application of supercritical airfoils can permit an increase in efficient cruise speed by delaying the transonic drag rise or can improve structural efficiency by increasing wing thickness without degrading cruise speed. Combining such an airfoil with wing sweep, configurational area ruling, forebody shaping, and optimization of the boattail-base-nozzle section may yield modest increases in range or, if desired, a decreased time-to-target at the same range. It was reported, however, that trade-off studies similar to these were made in the Tomahawk program (Ref. 6.6) and it was concluded that there was no single area where significant improvements could be made.

As pointed out in Item A-4, for long range missiles flying at constant altitude with large fuel loads, the lift should be adjusted during flight to account for the decrease in weight as fuel is depleted if the missiles are to continue to fly at optimum L/D. Thus a need exists for a capability to vary the in-flight aerodynamics to maintain a nearly optimum L/D ratio.

For supersonic cruise missiles, the preliminary designer could use a compilation of the parameter V(L/D) for the many possible air-breathing configurations (one, two, or four inlets located forward, mid-body, or aft) currently under investigation. Combined with this information must be an overall propulsion system figure-of-merit so that a combined aerodynamic and propulsion "efficiency" can be defined. Proper matching of airframe and engine as given in Item A-3 and optimal selection of speed, altitude, and aerodynamic configuration of Item A-4 should lead to considerable improvements in airframe performance. It should be noted that even though the selection process is highly mission-dependent some combined "efficiency factors" are needed to guide the designer's choice. Very little data are available on cruise missiles designed for high supersonic or hypersonic flight so that the area for research is quite broad. A fundamental investigation of potential L/D ratios for different classes of such cruise missiles (see Item A-5) is needed in order to make an assessment of the feasibility of the missiles for certain missions. The Air Force program discussed briefly in Sec. 4.3 has,

as one of its goals, the compilation of enough computational and experimental data on a wide variety of aerodynamic configurations (many non-conventional) to provide an upper bound to available L/D without the degradation that will result from consideration of other subsystems such as propulsion guidance, launcher, etc., or the requirements for low sensor signatures. These considerations will follow in later phases of that program.

The remaining two items, A-6 and A-7, do not describe areas where potential improvements may be made (since there are no existing hypersonic cruise missiles) but rather point out areas where research is needed in order to be able to proceed confidently to development of medium range cruise missiles in the hypersonic regime. The interaction between the air-breathing propulsion system and the aerodynamic configuration is expected to be a significant problem for both technologies. Simulation of the internal flow as well as the external flow at wind-tunnel scale needs attention. The complex flow field in the hypersonic and high supersonic regime also poses difficulties for the proper thermal design of such vehicles as well as the aerodynamic design for suitable stabili and control.

During the terminal phase of flight, it might be necessary to perform evasive maneuvers to achieve penetrativity to the target. These maneuvers may be achieved either by going faster or by providing a higher lift coefficient. Thus Item A-8 suggests development of means for providing a higher lift coefficient with minimum increase in RCS. Deployment of previously folded lifting surfaces, or changes in contour of already deployed surfaces could be considered, as well as operation at higher angles of attack. Operation at high angles of attack generally increases the severity of aerodynamic coupling of the angular modes of motion resulting in increased demands on the control system. Continued research is needed to understand and to predict the aerodynamic phenomena, to devise ways of reducing their adverse effects, and to develop improved methods for controlling the missile under such conditions (Item A-9).

6.2 Propulsion

As pointed out in Ref. 6.1, the inlet and exhaust ducts are essentially open cavity resonators with the engine (closed end) reflecting energy. Several possible camouflage methods for inlets are discussed in Ref. 6.8. As reported in Ref. 6.3, the inlets of the Hound Dog missile received a treatment of radar-absorbing material to reduce the radar cross-section of the missile. Some proposed configurations have the inlets and exhausts placed on the upper side of the missile in submerged locations in an attempt to lower the RCS. Thus, it would appear that Items P-1 and P-2 should be a prerequisite to the design of advanced strategic missiles. It is clear that some compromise is needed between good engine-airframe performance and low radar cross-section and a closely coordinated research effort is needed to acquire the data needed for such a compromise.

Item P-3 covers the general study of improvement in fuels for both air-breathing propulsion and solid rocket propulsion, a prime factor in range improvement. An unclassified survey of liquid fuel technology advances (from Ref. 6.9) shows only modest increases in density expected from hydrocarbons, going from the current 60-70 lbs./ft^3 to 70-75 lbs./ft.^{3*}. But carbon, aluminum, and boron slurries can provide density increases up to 110 lbs./ft.^{3*} with attendant increases in volumetric heating values. A summary of liquid fuel technology status is given in Fig. 6-5 taken from Ref. 6.9. In solid propellants (according to Ref. 6.9) significant increases in density, from .06-.07 lbs./in.^{3} to .08-.09 lbs./in.^{3*}, are to be expected through the use of high density metal fuels such as zirconium. A summary of solid fuel technology status is given in Fig. 6-6 taken from Ref. 6.9.

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*The units of Ref. 6.9 have been retained for clarity of the Figures. The conversions to SI units are:

$1 \text{ lb.wt./ft.}^3 = 4.9787 \times 10^{-1} \text{ kg/m}^3$

$1 \text{ lb.wt./in.}^3 = 8.6032 \times 10^{2} \text{ kg/m}^3$

$1 \text{ BTU/lb.wt.} = 7.4836 \times 10^{4} \text{ joules/kg}$

$1 \text{ BTU/liq.gal.} = 2.7871 \times 10^{5} \text{ joules/m}^3$

$1 \text{ lb.wt.sec./in.}^3 = 8.6032 \times 10^{2} \text{ kg sec/m}^3$

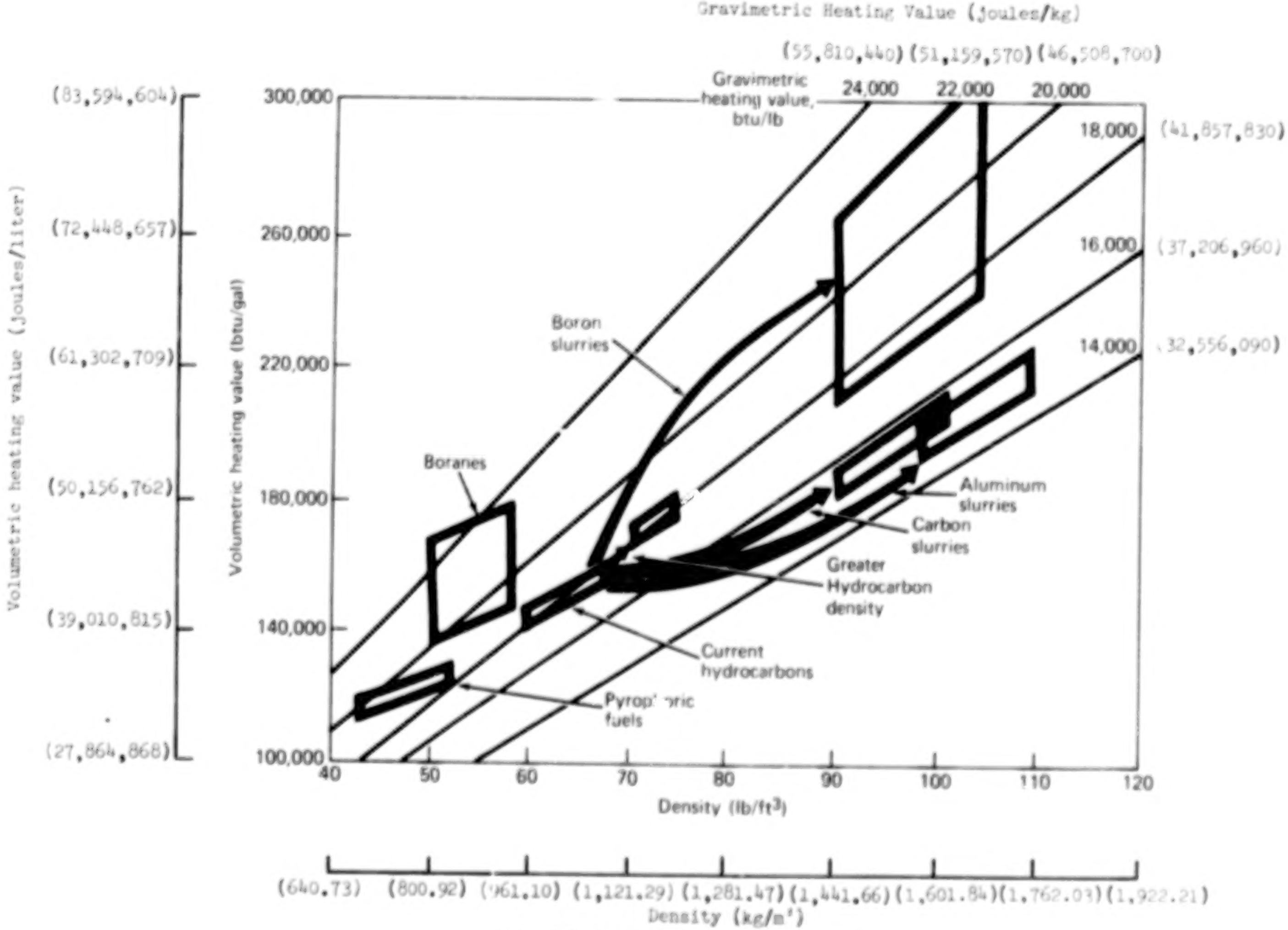

Fig. 6-5 Liquid fuel technology advances

(SI Units are shown in parenthesis)

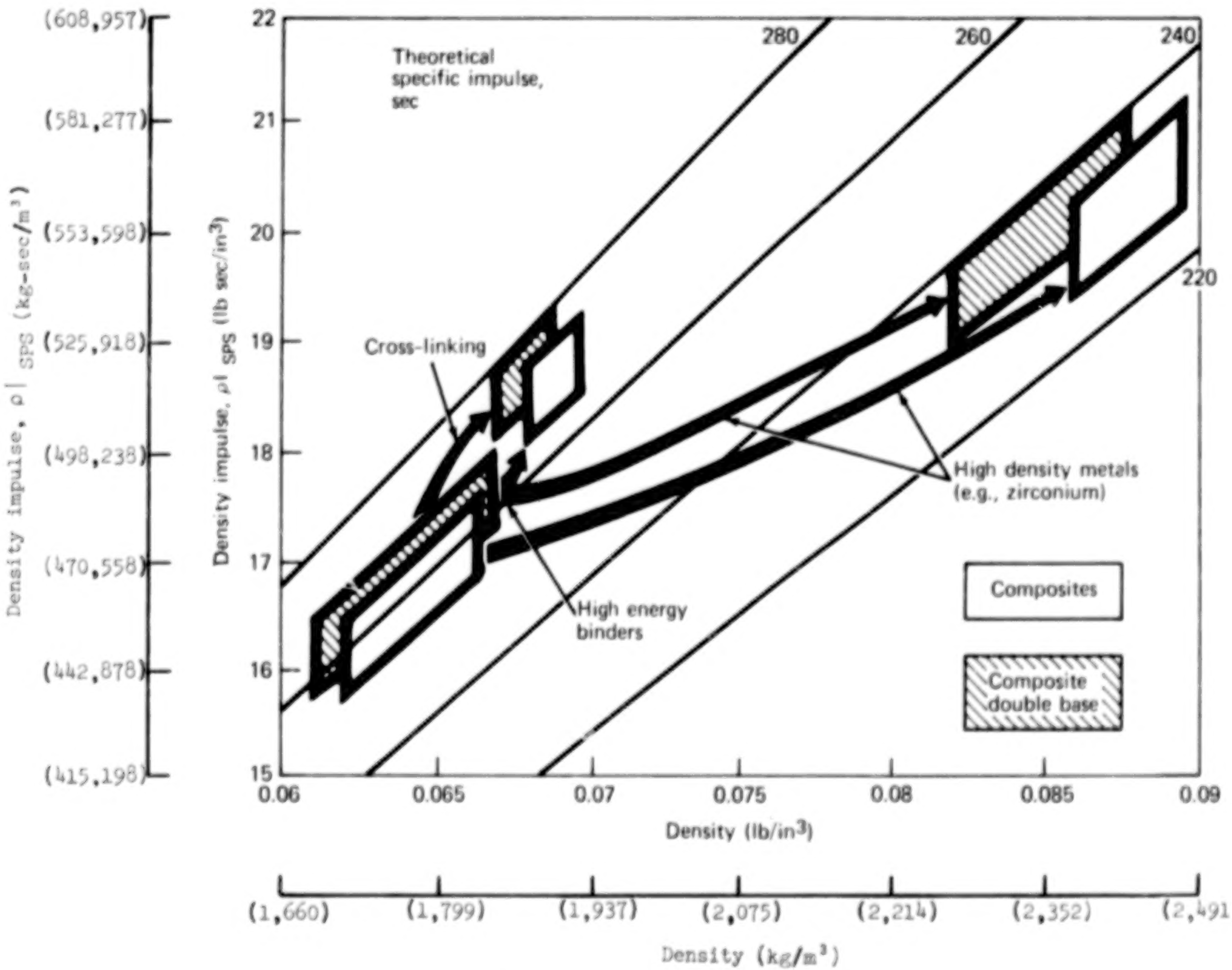

Fig. 6-6 Solid propellant technology advances

(SI Units are shown in parenthesis)

Some improvement in the physical characteristics are needed in order to be able to take advantage of the promising performance capabilities of the fuels. Improved combustion efficiency for the slurries must be achieved and fuel control and delivery systems must be developed to handle such suspensions efficiently. The solid propellants require some improvement in strength to achieve their full potential.

Although Item P-4 seeks improvement in both inlet and nozzle performance through use of variable geometry, the need for variable geometry in the nozzle section seems to be more urgent in that many integral rocket-ramjet (IRR) missiles are being considered for "cruise" missile applications as defined in Sec. 2. A simple two-position nozzle (one position for boost, the other for ramjet cruise) would appear to be more attractive for the IRR than a "blow-out" booster nozzle. In addition to mechanical complexity, blowing out the booster nozzle could be a significant give-away to searching radar. Perhaps even more attractive might be a nozzleless booster grain in the rocket chamber of the IRR as suggested by Item P-5, despite an expected loss in specific impulse and possibly in total impulse. Variable geometry, particularly for axially symmetric inlets, results in added design complexity for the improved performance expected through operation at nearly optimum conditions for most of the flight profile. Again it must be remembered that the suggestions of Item P-4 must be considered during the investigations connected with Items P-1 and P-2.

A further concern in the development of an integral rocket-ramjet is the smooth transition from rocket propulsion to ramjet propulsion with minimum loss of missile speed, Item P-6. The opening of the inlet ducts to the combustor and the rapid change from small rocket nozzle area to larger ramjet nozzle area are important phases (and significant design problems) in the operation of such an engine.

Another important consideration in the design of an integral rocket-ramjet engine is the optimum apportionment of weight to boost propellant and to sustainer fuel. Many inter-related design parameters must be considered in making this apportionment to achieve maximum performance.

The investigations proposed in Item P-7 are pointed toward getting improvements in engine performance by being able to design an inlet to perform adequately in other than a uniform flow field. Since such a design is

very much mission-related, there is a need for analytical techniques which can guide the development of the inlets and the placement of inlets relative to the rest of the airframe prior to the necessary testing period. Such an analytic and computational capability would contribute to improving range and maneuvering performance and would also be an asset in carrying out the studies of Item P-1.

Similarly, a computational capability is needed to aid in optimizing the aft section of the airframe including the nozzle (Item P-8). In the case of ramjet-propelled missiles there is generally not as great a payoff as for rocket-propelled missiles since the throat of the ramjet nozzle is relatively large so that base area is minimum and boattailing either may not be needed or may be minimal.

With the ever-increasing demands for better performance of propulsion systems, it is inevitable that operating temperatures will increase and methods must be available to take advantage of this means for increasing engine performance without severe weight penalties. The studies suggested in Item P-9 address this need. With engine operation at higher temperature, however, consideration must also be given to schemes for minimizing the increase in the infra-red signature while achieving the improvement in engine performance.

The work on improvement of turbojets and turbofans (Item P-10) has been recognized as a need for improving cruise missiles and, as discussed in Section 4.3, the Defense Advanced Research Projects Agency (DARPA) is supporting work in this area.

6.3 Structures and Materials

The improvement areas listed as Items S-1 and S-2 focus on the need to establish both a data base and analytic tools to trade off requirements for low RCS against structural efficiencies, thermal protection needs, and economic producibility. The overriding need to lower the electromagnetic signatures drives the demand for developing these two areas so that strategic systems analysts and missile designers may know what weight, performance, and cost penalties they will have to pay for a low RCS. An example has already been given in Fig. 6-2 of how the material of a wing panel affects the RCS. In this example, the fiberglass wing had a higher RCS by nearly an order of magnitude, on the average, than a metal wing. Hence, RAM applications to the fiberglass wing, reflecting additional weight, would be required to reduce its RCS to a desired level.

For supersonic and hypersonic missiles a similar need exists in the IR area as the emissivity-temperature characteristics of thermal protection systems must meet future requirements.

The growing technological promises of advanced composite materials using high strength, high modulus, low-density filaments in a compatible matrix should be harnessed to produce cheaper, lower weight structures, allowing more volume for fuel and/or payload as well as providing reduced electromagnetic and IR signatures. Items S-3 and S-4 are suggested as means to achieve these goals.

In comparing advanced composites with conventional airframe materials, one can use the mechanical and physical properties of the respective materials, namely, ultimate stresses, moduli of elasticity, and densities to calculate ratios of structural weight carrying the same loads, or inversely, the loads carried by the same weight of material. An illustration is given in Table 6-1 to show what such ratios might be if a 5.7 mil borsic/aluminum (0°, ± 45°) composite is used to replace 2219 aluminum alloy. The comparison is made for several types of elementary structural members whose usual design criteria and critical material parameters, K, are also listed in Table 6-1. The last two columns show, respectively, the ratio of load-carrying capability of the composite to that of the aluminum alloy for the same weight of material

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TABLE 6-1

Borsic/Aluminum Composite vs. Aluminum Alloy

Type of Structural Element	Design Criterion	Critical Material Parameter, K	Load Ratio at Same Weight, K_C/K_A	Weight Ratio at Same Load
1. Tension member	Ultimate tensile strength	F_{tu_L}/ρ	2.41	0.41
2. Compression member	Ultimate compressive strength	F_{cu_L}/ρ	3.91	0.26
3. Flat plate	Buckling strength in compression	$E_{c_L}^{1/3}/\rho$	1.31	0.76
4. Circular cylinder	Buckling strength in compression	$E_{c_L}^{1/2}/\rho$	1.50	0.67
5. Circular cylinder	Buckling strength in bending	$E_{t_L}^{1/2}/\rho$	1.41	0.71
6. Circular cylinder	Buckling strength under collapsing pressure	$E_{c_T}^{1/3}/\rho$	1.24	0.81
7. Circular cylinder	Bending stiffness	E_{t_L}/ρ	1.99	0.50

F_{tu} = ultimate tensile stress

F_{cu} = ultimate compressive stress

E_t = modulus of elasticity in tension

E_c = modulus of elasticity in compression

ρ = density

Subscripts

L = longitudinal

T = transverse

C = composite

A = aluminum alloy

K_C = material parameter for composite

K_A = material parameter for aluminum alloy

(or K_C/K_A) and its inverse, that is, the weight ratio of the two materials carrying the same load. The densities of the two materials are essentially the same so that the density ratio is taken as unity. In all cases shown, the composite is a more efficient load-carrying material.

A brief analysis was also made of the effect of replacing the conventional aluminum alloy structural airframe components of the current Tomahawk missile with this advanced composite material, namely, 5.7 mil-diameter Borsic/Aluminum with a [0°/± 45°]-ply orientation. This application would reduce the empty missile weight some 15%, and increase the useable fuel volume about 4%, resulting in an increase of cruise range of about 10%. The assessment of economic and production implications of such changes would have to be made by experts in the production and handling of composite structures.

Advanced composite materials are also included in Items S-1 and S-2 as possible signature-reducing materials and in Item P-9 as improved insulators and thermal protection materials for engines operating at higher temperatures which could result in improvements in specific fuel consumption.

The potential to exploit the promises of new materials and structural components will rest on developing the appropriate new structural-analysis techniques and material-processing methods. Items S-1 and S-4 were listed to fill such needs because without these new tools, the anticipated improvements in signature reductions, thermal protection, and weight and cost reduction can neither be promised nor achieved.

Item S-5 suggests a continuing research effort to assure structural integrity and material transmittability for cruise flight in rain, ice, snow and particulate environments. Similar concerns exist even in clear air at sustained high supersonic and hypersonic speeds. Item S-6 recommends that the environment of any launch constraint which imposes dynamic, inertial, and thermal loads and/or surface contaminations needs to be defined more thoroughly and in greater detail by analytic means supported by properly instrumented and selected test programs. Otherwise, conservative environments will be defined out of ignorance, resulting in unnecessary extra weight which degrades performance, such as range and maneuverability.

6.4 References

6.1 W. F. Bahret, "Introduction to Radar Camouflage(U)," Paper #1, Confidential, AFAL-TR-75-100,* December 1975.

6.2 J. D. Kelly, "Configuration Design for Low RCS (U)," Paper #3, AFAL-TR-75-100, December 1975.

6.3 G. A. Taylor, "Missile Radar Camouflage Applications (U)," Paper #18, Confidential, AFAL-TR-75-100, December 1975.

6.4 C. Mentzer, "Non-Specular RCS Reduction (U)," Paper #5, Confidential, AFAL-TR-75-100, December 1975.

6.5 T. G. Ayers, "Supercritical Aerodynamics Worthwhile over a Range of Speeds," Astronautics and Aeronautics, August 1972.

6.6 R. S. MacKenzie, "Tomahawk Cruise Missile - System Integration Stage Final Engineering Report (U)," General Dynamics Convair Report GDC, NCM-7028, April 1977, Confidential.

6.7 NAVWEPS Repprt 1488 (Volume 3), Handbook of Supersonic Aerodynamics, Section 8, Bodies of Revolution, October 1961.

6.8 R. D. Strattas, "Duct RCS Reduction (U)," Paper #13, Confidential, AFAL-TR-75-100, December 1975.

6.9 McDonnell Douglas Astronautics Co., "SLRMIS Final Oral Review (U)," April 1978 (SECRET).

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* Several references in this report are made to the "Proceedings of the 1975 Radar Camouflage Symposium (U)," December 1975, AFAL-TR-75-100, Secret. Papers range in classification from Unclassified to SECRET.

7. Suggested Technology Programs in Aerodynamics, Propulsion, and Structures

7.1 Rationale for Suggested Technology Programs

The list of potential areas of technological improvements for future cruise missiles can easily grow to some twenty or more as shown in the preceding Sections, considering only the three fields of aerodynamics, propulsion, and structures and materials. Other technology areas important to missile systems, such as guidance and control, sensors, computers, etc., will add more areas of desired improvements. With such a large list of candidate topics for research and development, it becomes important to identify a few areas considered to be most critical to future missile systems and to suggest a program of activities in their support. The other potential areas, although desirable from a technological standpoint, may have less direct impact on performance of future missile systems.

The general projections of future requirements given in the preceding Sections indicated an overriding interest in improvements in penetrativity, followed next by range (and time-to target) improvements and then by higher maneuvering capabilities. These priorities are set by the specific missions and the particular missile system under consideration. For strategic missions, clearly penetrativity is uppermost on the list of priorities. For tactical, defensive, air-to-air or surface-to-air missions, however, maneuverability and range will be the drivers while penetrativity considerations in the form of signature reduction may not be meaningful at all.

Although economic considerations will always be present and are frequently the primary factor, the specific areas of cost reduction, simplicity of design and minimal logistic requirements will be assigned secondary emphasis in this list of technology research suggestions. In addition to responding to future technological requirements, these suggested research programs must be designed to provide the greatest help to systems analysts, and conceptual designers who must make the trade-off studies leading to advanced missile concepts. As presented graphically in Chart 7-1, the design task starts with an assigned mission for one of the DOD Services, and a projection of the threats which may attempt to prevent carrying out the assigned mission.

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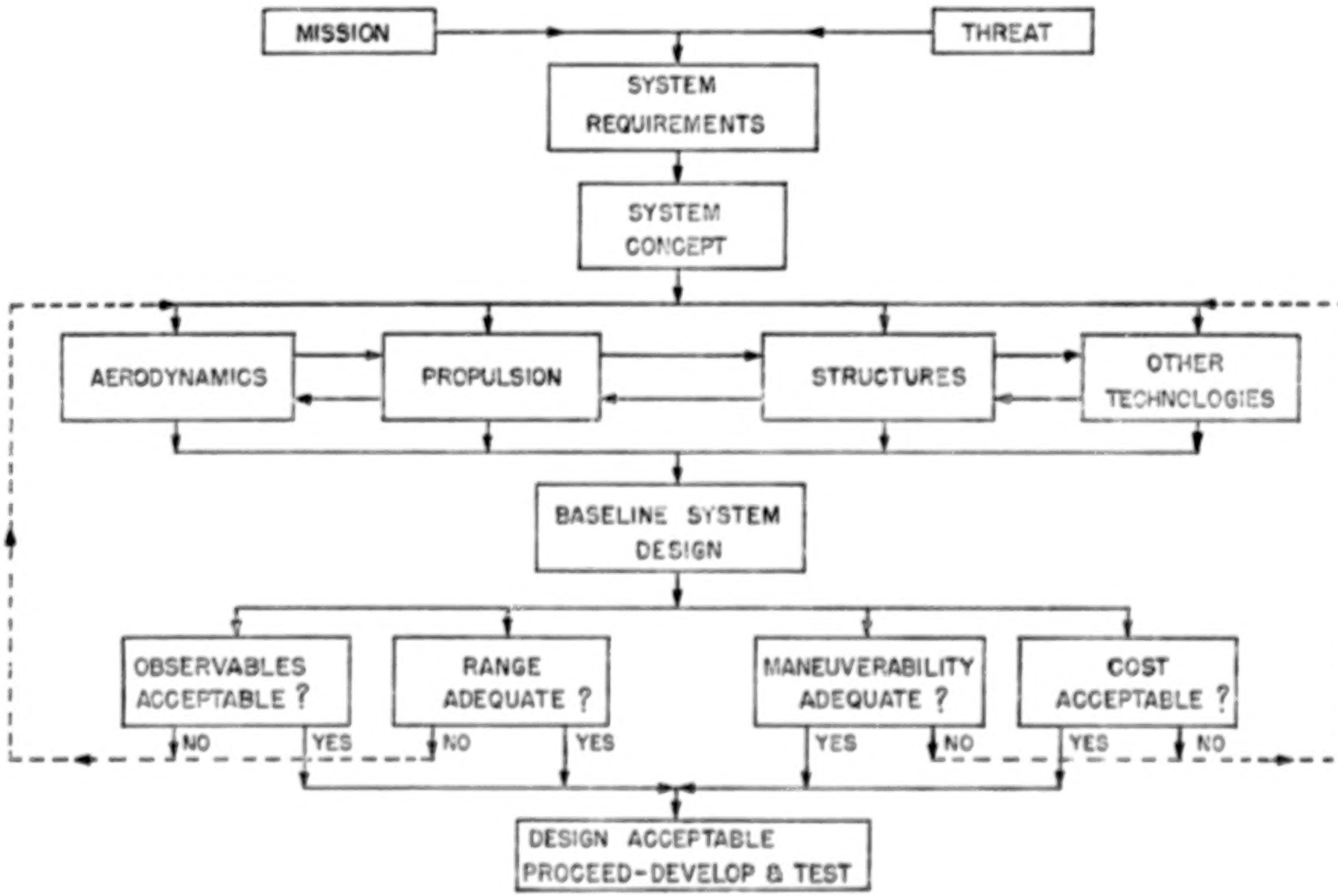
CHART 7-1 SCHEMATIC DIAGRAM - ITERATIVE DESIGN CYCLES - MISSILE SYSTEM OPTIMIZATION



The mission-threat analyses lead to requirements for a system to insure that the mission can be carried out in the presence of enemy threats, countermeasures, etc. For a mission requiring a missile system, the preliminary system requirements, which are fundamental guides to the design concept, eventually place certain restrictions on the choice of elements for the missile system. The desire to get optimum system performance for a given system cost then leads to trade-off studies among the several technologies. Usually a baseline system, embracing the major physical concepts deemed necessary to achieve the mission, starts the preliminary design cycle. To take advantage of technology improvements by means of trade-off studies, the design iteration then goes through the several loops of Chart 7-1. Based on the analyses of the preceding Sections, it is expected that there will be decision points as shown under observables, range, maneuverability, and cost. The research programs suggested in this Section should be structured to provide the data in the form that would facilitate this iterative process and the associated trade-off studies and so lead to an acceptable system design ready to go to further development and testing. In the trade-off studies, the performance of each technology can be judged by some "Measures of Merit," parameters which describe the capability of the technology in a quantitative manner. (These are illustrated in Charts 7-2, 7-3, and 7-4 to be discussed later in this Section.) Particular attention should be called to the fact that no matter where the design is rejected for non-compliance with a requirement, the iterative procedure requires that the revised system be checked again for compliance with all other requirements. Thus, if a change is made in propulsion in order to provide adequate range, the revised propulsion system must again be found acceptable to the observables requirement, maneuverability requirement, and cost limit. The most desirable output of the research programs would be trade-off equations, charts, or computer programs which relate the parametric design changes in the system to performance changes in the affected technologies. These relations could be some type of performance exchange ratios between technologies. For example, application of radar-absorbing material to an inlet may result in a reduction in radar cross-section, accompanied by a change in aerodynamic drag, a change in pressure recovery and mass capture of the inlet, and a change in weight and

and volume of the engine. The exchanges in performance resulting from the design modification needed to reduce RCS should be available if a meaningful trade-off study is to be made. In fact, such information is necessary regardless of the priority one might put on the decision points of Chart 7-1.

In the following Sections, research programs are suggested in the three technologies (Aerodynamics, Propulsion, Structures) based on the perceived importance of such programs to the future performance of cruise missiles.

Within each technology there exist performance parameters or characteristics which can be used as measures of merit to determine if the resulting system performance is consistent with the specific requirements according to Chart 7-1 considering all technologies involved. Every measure of merit is influenced by one or more physical or geometric components of the airframe which need to be varied over reasonable ranges in the research programs to provide the data on performance exchange ratios needed in the design optimization process. Hence, in the next three sub-sections each technology is broken down into measures of merit and missile components involved. Also indicated are identifying symbols (e.g., A-2) of those research topics from Section 5 which are judged to be of greatest benefit for improving the performance of future systems based on the relative merits discussed in Section 6.

7.2 Program to Improve Penetrativity

The analyses which led to the summary Chart 5-1 point to an area embracing many inter-related technologies in which research is needed. In Chart 7-2 the improvement areas suggested in Chart 5-1 are combined with the trade-off requirements indicated in Chart 7-1. This chart shows a relation between a cruise missile performance area (penetrativity in this case) and desired performance parameters, called Measures of Merit here, in each of the technologies and suggests individual contributing missile components and parameters in these technologies. Not shown, for instance, are the iterative and two-way paths between the three airframe technologies and the signature technology governing penetrativity, as well as some direct, two-way coupling between the individual technologies. The chart is intended to be very general. For specific mission applications and speed regimes, other parameters and components may be more appropriate and should be developed as the need arises. Although Mach number is not given in the chart, the immediate need would be for the subsonic cruise missiles and any improved versions of them. In view of the time required to establish such a comprehensive program, however, it might be more advantageous to address the supersonic and hypersonic regimes if the results of the investigation are to have a suitable impact on future designs.

As to the subsonic regime, there may already exist a large amount of unrelated data from the current cruise missile programs which could be assembled. Such an approach would indicate if there exist some areas not covered systematically by adequate trade-off data which could then be filled in by a subsequent program of research in the subsonic aerodynamics, propulsion, and structures areas.

For the aerodynamics-signature technologies (Columns 2 and 5 of Chart 7-2), a systematic study of radar cross-section (or other signature) and aerodynamic performance characteristics of airframe elements (body, wing, stabilizing and control surfaces) is suggested to provide information needed for trade-off of stealth with aerodynamic performance. The radar cross-section measurements should be made over an appropriate range of aspect angles (e.g., for body alone, nose aspect ± 30°, side aspect ± 30°, rear aspect ± 30°).

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CHART 7-2 Penetrativity Performance and Technology Areas

1 Technologies	2 Aerodynamics	3 Propulsion	4 Structures and Materials	5 Signature
Measures of Merit	• Aerodynamic Forces and Moments • Stability Margins • Control Effectiveness	• Inlet Drag, Pressure Recovery, Air Capture • Exit Nozzle Net Thrust	• Weight • Volume • Ease of Manufacture	Radar, IR, Optical as Function of Aspect Angle, Wave Length, Polarization, etc.
Missile Components	• Body • Surfaces • Full Configurations	• Inlet(s) • Exit Nozzle(s) • Full Configurations	• Conventional Structural Elements + Absorbing Material (e.g., RAM) • Absorbing Primary Structural Elements (e.g., RAPS) • Fully Assembled Configurations	
Recommended Research Topics (Identified in Sec. 5)	A-1 A-3	P-1 P-2 (A-3)	S-1 S-2	

The wave length must be chosen judiciously to conform with whatever detail is under investigation. In the aerodynamics technology, measurements or calculations are needed of the most significant aerodynamic performance characteristics associated with parametric changes of configuration components. For example, drag coefficient would be one measure of merit associated with variations in nose shape or wing sweepback angle. Combination of the components including the full configurations would identify the effects of interference, both aerodynamic and electromagnetic. The work on bodies should include bodies of non-circular cross-section and non-constant cross-sectional area as well as the more usual shape changes of nose and boattail on cylindrical bodies. For lifting and control surfaces, consideration should be given to wrap-around surfaces whose curvature provides certain packaging advantages and to thick wings of delta or clipped delta planform which serve as both body and lifting surface. When the bodies and surfaces are combined, resulting in corners, either filleted or unfilleted, the advantage of favorable aerodynamic interference must be weighed against the possible detrimental radar reflections from the corners.

A fundamental work unit that merits consideration is the study of a relatively conventional full missile configuration with its build-up components so that one could isolate the contributions (both aerodynamic and electromagnetic) from each configuration component (body, wings, tails or canards) and the mutual interferences (body-wing, body-tail, wing-tail, wing-wing, tail-tail, etc.). Depending on the results of such a basic investigation, one might then vary the parameters of the components to see if substantial pay-offs might be revealed in one technology with relatively minor losses in the other.

For the propulsion technology, a similar trade-off study is recommended between inlet and nozzle performance and sensor signature as shown in Columns 3 and 5 of Chart 7-2. In this case the measurements (or calculations) would involve inlet cowl drag, pressure recovery, air mass capture, and net thrust of the combination of nozzle, boattail, and base. In addition to the shape of the inlet (round, semi-round, oval, rectangular, etc.) and the presence of an inner body, one should also consider the shape and location of ducting leading to the combustor. Likewise, the location of the inlets (as airframe components) relative to the body or wing is an important consideration.

If appropriate, signature contributions from particular engine-fuel combinations may have to be included.

Again a fundamental work unit that should merit consideration would be a full air-breathing configuration with its build-up components and mutual interferences as discussed above for the aerodynamic case (which implied non-airbreathing propulsion).

The structures and materials technology tasks listed in Columns 4 and 5 of Chart 7-2 must first provide the tools needed to design and build the signature-effective configurations and critical components thereof derived in the aerodynamic and propulsion programs described above. Secondly, this work unit should develop means for determining where and how signature reducing materials (such as RAM, IR coatings, etc.) may be most effectively applied locally or overall and what the weight, volume, and design penalties would be. Thirdly, another trade-off question needs to be answered, namely, what is more effective from overall design considerations and signature suppression, a conventional primary structure with spot treatment of absorbing materials, or an integrated signature-absorbing primary structure (e.g., RAPS)? Clearly, the development of new materials should be an essential component of this research as it is a slow and tedious process to provide for the hoped-for absorbing qualities without losing other desirable physical and mechanical properties.

From the potential areas of technology advances that were listed in Section 5, the research topics that seem most likely to lead to improvements in penetrativity can be summarized as

A-1, A-3 in Aerodynamics,

P-1, P-2 in Propulsion, and

S-1, S-2 in Structures and Materials.

7.3 Program to Improve Range

An analogous outline of a suggested program to provide useful approaches to range improvement is shown in Chart 7-3. The trade-off coupling among aerodynamics, propulsion, and structures now involves those measures of merit and airframe components which affect range (e.g., factors in the Breguet range equation) and time of flight to the target as functions of cruise altitude, speed, and angle of attack.

In this research area the effect of speed is most important and the subsequent discussion will recognize two distinct speed regimes, subsonic and supersonic-hypersonic. In the subsonic regime the development of turbo-engines with better specific fuel consumption (as presently sponsored by DARPA, and reported briefly in Sec. 4) and the development of advanced fuels are the most promising areas. Next in potential pay-off might be the use of advanced composite materials for weight reduction (as noted in Sec. 6). It would appear that any gains in range from aerodynamic improvement would be from several small gains by applying to the full configuration each of several technology improvements already available (such as the supercritical wing, area ruling, nose shaping, etc.). Except for propulsion, none of the other technologies seem to warrant a special research program.

In the case of the supersonic and hypersonic cruise missiles, again the major gains are likely to be attained in the area of propulsion. The most probable propulsion system will be the integral rocket-ramjet. There are already several such propulsion systems in various stages of development. Although a parametric investigation of these mission-dependent systems is probably unworkable, a limited airframe-engine integration study of one or two generic types of such configurations aimed at achieving beneficial mutual interference would be useful in showing an approach for improving range.

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CHART 7-3 Range Performance and Technology Areas

1 Technologies	2 Aerodynamics	3 Propulsion	4 Structures and Materials
Measures of Merit	• Lift-Drag Ratio, L/D • Cruise Efficiency V(L/D)	• Specific Fuel Consumption, SFC • Propellant Specific Impulse, I_{SP} • Liquid Fuel Heating Value Per LB.	• Empty Weight, W_E • Volume
Missile Components	• Integral Rocket-Ramjet Configurations	• Fuel • Inlets, Nozzles • IRR Configurations	• Primary and Secondary Structural Elements • Combustor Liners
Recommended Research Topics (Identified in Sec. 5)	A-3	P-3 P-4 P-5	S-4 (P-9)

More generally applicable results may be obtained from the research topics noted in Chart 7-3 under Propulsion and Structures, which also relate to integral rocket-ramjet propulsion systems. The development of rocket propellant grains of greater structural integrity is a primary need for the higher performance rockets which will be operating at higher pressure. Likewise, further development of the high density slurry fuels is an important research area so that the designer can get maximum fuel energy in a given volume.

A longer range program with potentially high pay-off is the development of a nozzle-less rocket whose grain is shaped to provide an efficient nozzle contour throughout the burning period. As the booster for an integral rocket-ramjet, it could simplify the design for the rocket-to-ramjet transition by eliminating the need for mechanical removal of a booster nozzle insert.

A shorter range research program would be the development of a multi-position nozzle which could optimize thrust throughout the missile trajectory. A sub-group of such nozzles would be a two-position nozzle, one position for boost-thrust optimization, the other for sustain-thrust optimization.

In the area of structures and materials two key development areas are promising, namely, development of improved insulating materials for combustor liners to permit engine operation at higher temperatures (listed as P-9 under Propulsion in Section 5) and development and application of advanced composite materials with high strength/weight ratios to replace the metals now being used.

In summary, the technology areas of Section 5 which seem most desirable to pursue to achieve improvement in range are

A-3 in Aerodynamics,
P-3, P-4, P-5, P-9 in Propulsion, and
S-4,(P-9) in Structures and Materials.

7.4 Program to Improve Maneuverability

A program to improve maneuverability, both lateral and axial, is suggested in Chart 7-4. As pointed out in previous Sections, terminal performance of a cruise missile can be enhanced either by a faster run-in to the target or by increased maneuvering capability. For the subsonic case, the increased maneuver might be achieved by deployment of efficient high lift devices as required. Generally, the supersonic and hypersonic missiles have an adequate reserve of kinetic energy which can be converted to maneuvering gees, even with less efficient lifting devices, by resorting to higher angles of attack. Operation at high angles of attack, however, may pose problems to the aerodynamic control system in the form of adverse coupling among the angular modes of motion and to the propulsion system in less efficient operation of the inlets. Therefore, work is needed to further the understanding and control of adverse dynamic coupling at high angles of attack and to develop inlets which are less sensitive to angles of attack or yaw.

Improved axial maneuverability can be achieved off the launcher with higher energy rocket propellants and throughout the flight envelope with higher performance fuels.

In the structures and materials area, more complete data are needed on the performance of advanced composites at elevated temperatures and on criteria for defining failure of structural elements using composites so that designers will feel confident in applying these materials at higher speeds.

It should be recognized, in addition, that technologies other than those listed in Chart 7-4 have a major impact on maneuverability and terminal accuracy. For example, the guidance and control laws and mechanization, the sensors, computers, data processors, etc., all have an effect on such performance. In some cases they are very closely related to the three principal technologies of this report. An illustration of this was given in Item S-5 of Section 5 which emphasized the important interaction in sensor windows between material and structural integrity and their transmittibility under adverse environmental conditions. A joint research effort involving structures, thermodynamics, materials, and sensor (electromagnetic, infra-red, optical) window performance is needed to ascertain what limitations exist on sensor domes during high speed flight in an adverse environment.

CHART 7-4 Maneuverability Performance and Technology Areas

1 Technologies	2 Aerodynamics	3 Propulsion	4 Structures and Materials
Measures of Merit	• Maximum Lateral g's • Dynamic Coupling	• Maximum Axial g's • Thrust	• Weight • Sensor Window Integrity
Missile Components	• High Lift Devices • Full Configurations	• Inlets Insensitive to Angles of Attack and Yaw	• Advanced Composite Structural Members for High Temperatures and High Loads • Sensor Windows
Recommended Research Topics (Identified in Sec. 5)	A-8 A-9	P-3 P-7	S-3 S-5

Thus the topics from Section 5 most likely to contribute to improvement in missile maneuverability are

A-8, A-9 in Aerodynamics,

P-3, P-7 in Propulsion, and

S-3, S-5 in Structures and Materials.

7.5 General Research Programs

In the hypersonic speed regime it is not possible to identify special programs intended to improve performance of cruise missiles, even using the broad definition of cruise missiles given in Section 2, since only limited research has been done in this regime and no such missile systems exist. The areas listed in Section 5 under Items A-5, A-6, and A-7 do require some attention if the hypersonic regime is to be exploited in the future. In particular, methods of simulating hypersonic air-breathing missiles at model scale, allowing for viscous effects, is expected to be a key research area.

8. Summary and Recommendations

In this report the assessment of the impact that technology advances in aerodynamics, propulsion, and structures will have on cruise missile performance is based on the premise that any research in these areas must be planned and implemented such that the synergistic contributions from these technologies to the missile performance are evident at all times within the constraints of specific mission objectives. This premise means that each element of a research program in any of the technologies under consideration must be identified not only in terms of its own contribution and effect on the overall missile performance but also in terms of the specific interactions it has with the significant performance parameters of the other technologies. In this manner, the missile designers and system planners will have the necessary input data for meaningful trade-off analyses.

The research topics suggested herein have been derived from an analysis which recognized these interactions. First, the missile system requirements were categorized in terms of three major performance characteristics: Penetrativity, Range, and Maneuverability. These characteristics were, in turn, related to the contributing technologies of Aerodynamics, Propulsion, Structures and Materials, and others. Several research areas were listed which could contribute to improved performance. The relative merits of these areas were then discussed in terms of which ones might have the greatest impact on improving the performance of cruise missiles.

The research topics listed below emerge from this analysis. They are recommended for consideration as their outputs are expected to have the greatest influence on the design of future cruise missiles with improved performance characteristics. In each technology area, two topics are starred (*) to indicate that they are considered the top priority items in the listing.

Recommended Research Topics

Aerodynamics	A-1*	Aerodynamics-Signature Trade-off
	A-3	Airframe-Engine Integration
	A-8	Deployable High-Lift Devices
	A-9*	High α Aerodynamics
Propulsion	P-1*	Inlet-Signature Trade-off
	P-2	Nozzle-Signature Trade-off
	P-3*	Fuel Development
	P-4	Variable Geometry Nozzles
	P-5	Nozzleless Rockets
	P-7	Inlets Insensitive to Angle of Attack
	P-9	Combustor Insulating Materials
Structures and Materials		
	S-1	Analysis Methods for Structural Trade-offs
	S-2*	RAM-coated Structure vs. Radar Absorbing Primary Structure
	S-3	Properties of Advanced Composite Materials
	S-4*	Development and Application of Composites
	S-5	Environmental Effects on Sensor Domes

* Two areas have been selected from each technology as priority items. The identifying symbols (e.g., A-1) refer to the more complete statements given in Section 5.

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15. Supplementary Notes

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16. Abstract

An assessment is presented of areas in the technologies of aerodynamics, propulsion, and structures and materials in which research advances might lead to performance improvements in cruise missile systems over the full speed range, subsonic to hypersonic.

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